

Spectrophotometric measurement of the Extragalactic Background Light

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Abstract. The Extragalactic Background Light (EBL) at UV, optical and NIR wavelengths consists of the integrated light of all unresolved galaxies along the line of sight plus any contributions by intergalactic matter including hypothetical decaying relic particles. The measurement of the EBL has turned out to be a tedious problem. This is because of the foreground components of the night sky brightness, much larger than the EBL itself: the Zodiacal Light (ZL), Integrated Starlight (ISL), Diffuse Galactic Light (DGL) and, for ground-based observations, the Airglow (AGL) and the tropospheric scattered light. We have been developing a method for the EBL measurement which utilises the screening effect of a dark nebula on the EBL. A differential measurement in the direction of a high-latitude dark nebula and its surrounding area provides a signal that is due to two components only, i.e. the EBL and the diffusely scattered ISL from the cloud. We present a progress report of this method where we are now utilising intermediate resolution spectroscopy with ESO's VLT telescope. We detect and remove the scattered ISL component by using its characteristic Fraunhofer line spectral signature. In contrast to the ISL, in the EBL spectrum all spectral lines are washed out. We present a high quality spectrum representing the difference between an opaque position within our target cloud and several clear OFF positions around the cloud. We derive a preliminary EBL value at 400 nm and an upper limit to the EBL at 520 nm. These values are in the same range as the EBL lower limits derived from galaxy counts.

Unit: We will use in this paper the abbreviation $1 \text{ cgs} = 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Å}^{-1}$

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1. Introduction

The importance of the Extragalactic Background Light (EBL) for cosmology has long been recognized (e.g. Partridge & Peebles 1967). The EBL at UV, optical and near infrared wavelengths consists of the integrated light of all unresolved galaxies along the line of sight plus any contributions by intergalactic gas and dust and by hypothetical decaying relic particles. A large fraction of the energy released in the Universe since the recombination epoch is expected to be contained in the EBL. An important aspect is the balance between the UV-NIR and the far infrared EBL: what is lost by dust obscuration in the UV-NIR will re-appear in the FIR. Some central, but still largely open astrophysical problems to be addressed through EBL measurements include the formation and early evolution of galaxies and the star formation history of the Universe. Because of the foreground components, much larger than the EBL itself, the measurement of the EBL has turned out to be a tedious problem. As a consequence we lack a generally accepted measured value of the optical EBL. For a review see Leinert et al. (1998).

Recently, Bernstein et al. (2002) have announced “the first detection” of the EBL

at 300, 550, and 800 nm. They used a combination of space borne (HST) and ground based (Las Campanas) measurements in their method. However, Mattila (2003) has argued that they neglected important effects of the atmospheric scattered light and had a problem with the inter-calibration of the two telescopes used. Therefore, the claim for a detection of the EBL appeared premature. After reanalysis of their systematic errors Bernstein et. al. (2005) and Bernstein (2007) came to the same conclusions which they formulated as follows: “... the complexity of the corrections required to do absolute surface (spectro)photometry from the ground make it impossible to achieve 1% accuracy in the calibration of the ZL.” and “...the only promising strategy ... is to perform all measurements with the same instrument, so that the majority of corrections and foreground subtractions can be done in a relative sense, before the absolute calibration is applied.”

In this situation it is highly desirable to obtain a measurement of the EBL with an independent method which utilises one and the same instrument for all sky components and is virtually free of the large foreground components, the Airglow (AGL), Zodiacal Light (ZL) and tropospheric scattered light.

2. The dark cloud shadow method.

We have been developing over several years a method for the measurement of the EBL which utilises the screening effect of a dark nebula on the background light (see Mattila 1990 for a review and previous results). A differential measurement of the night-sky brightness in the direction of a high galactic latitude dark nebula and its surrounding area, which is (almost) free of obscuring dust, provides a signal that is due to two components only: (1) the EBL and (2) the diffusely scattered starlight from interstellar dust in the cloud (and to smaller extent also in its surroundings). All the large foreground components, i.e. the ZL, the AGL, and the tropospheric scattered light, are completely eliminated (see Fig. 1a). The direct starlight down to ~ 21 -23 mag can be eliminated by selecting the measuring areas with the help of deep images. At high galactic latitudes ($|b| > 30$ deg), the star density is sufficiently low to allow blank areas of sufficient size to be easily found. Models of the Galaxy show that the contribution from unresolved stars beyond this limiting magnitude is of minor or no importance (Mattila 1976). If the scattered light from the interstellar dust were zero (i.e. if the grain albedo $a = 0$), then the difference in surface brightness between a transparent comparison area and the dark nebula would be due to the EBL only, and an opaque nebula would be darker by the amount of the EBL intensity (dashed line in Fig. 1c). The scattered light is not zero, however. A dark nebula in the interstellar space is always exposed to the radiation field of the integrated Galactic starlight, which gives rise to a diffuse scattered light (shaded area in Fig. 1c). Because the intensity of this scattered starlight in the dark nebula is equal to or larger than the EBL, its separation is the main task in our method. The key issue in the dark cloud method is to get a reliable estimate for the scattered light. This can be achieved by means of spectroscopy. With intermediate-resolution spectroscopy ($R \approx 800$) it is possible to determine the strengths of the stronger Fraunhofer lines in the spectrum of the excess surface brightness of the dark cloud. Spectroscopic measurement of a faint surface brightness signal, only 1 – 10% above the dark sky level has been possible with the VLT/FORS long slit spectroscopy.

Target cloud and positions. The high galactic latitude dark nebula Lynds 1642

($l = 210.9$ deg, $b = -36.7$ deg) has been chosen as our primary target. It has a high obscuration ($A_V > 15$ mag) in the centre and areas of good transparency ($A_V \approx 0.15$ mag) in its immediate surroundings within $\sim 1 - 2$ deg. Its declination of -14.5 deg allows observations at low airmasses from Paranal. Our measuring positions ($2'\phi$) for intermediate band photometry (Mattila and Schnur 1990) are shown in Fig. 2 as circles and the positions where photometry and VLT/FORS long slit spectra ($2'' \times 6.8'$) were taken, as squares. Differential measurements with repeated ON/OFF switching cycle of ~ 0.5 h were used to eliminate airglow variations. The spectral range was $360 - 600$ nm and the resolution $\Delta\lambda = 1.1$ nm. Stamps of $10'' \times 10''$ size centered on the VLT/FORS positions, adopted from DSS blue plates, are shown in the margins: the dark central position #8 ($A_V > 15$ mag) in upper left, followed clockwise by the two intermediate opacity positions #9 and 42, and then the transparent OFF positions. Two observed spectra “dark nebula minus surrounding sky” are shown in Fig. 3: One is for the opaque central position #8 with $A_V > 15$ mag, the other for the average of two intermediate opacity

positions, #9 and #42 with $A_V \approx 1$ mag. The crosses show the results of previous intermediate band photometry by Mattila and Schnur (Mattila 1990) with error bars and filter band widths indicated. The spectra have been re-scaled by a multiplicative factor to adjust them to the more reliably calibrated photometry. The intermediate opacity positions are used to validate the model of Galactic starlight spectrum, needed to accurately separate the Galactic contribution from the observed spectrum “dark position minus clear sky”. In combination with the dark central position they enable us to disentangle the effects of extinction and reddening by dust from the spectral shape of the Galactic starlight.

Component separation method. Our separation method utilises the difference in the spectra of the EBL and the integrated Galactic starlight (see Fig 1d). While the scattered Galactic starlight spectrum has the characteristic stellar Fraunhofer lines and the discontinuity at 400 nm the EBL spectrum is a smooth one without these features. This can be understood because the radiation from galaxies and other luminous matter over a vast redshift range contributes to the EBL, thus washing out any spectral lines or discontinuities. The spectrum of the integrated Galactic starlight can be synthesised by using the known spectra of representative stars of different spectral classes, as well as the

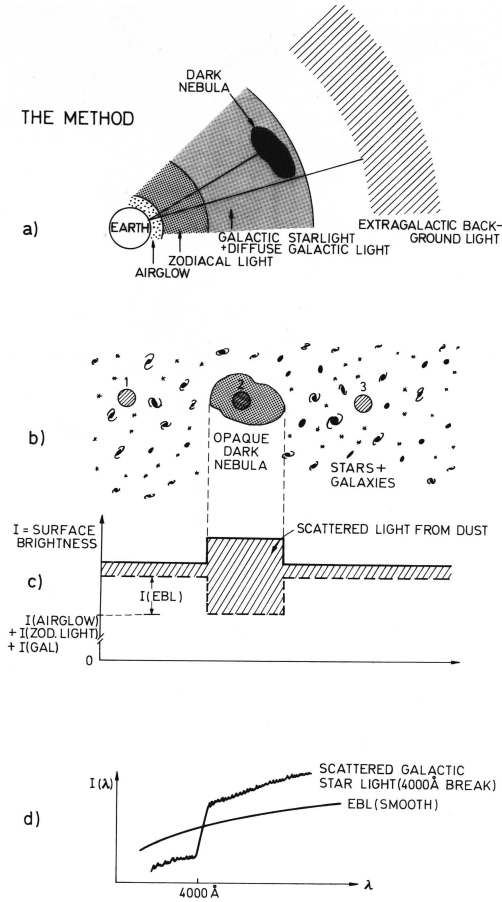


Figure 1. EBL measurement with the dark cloud shadow method

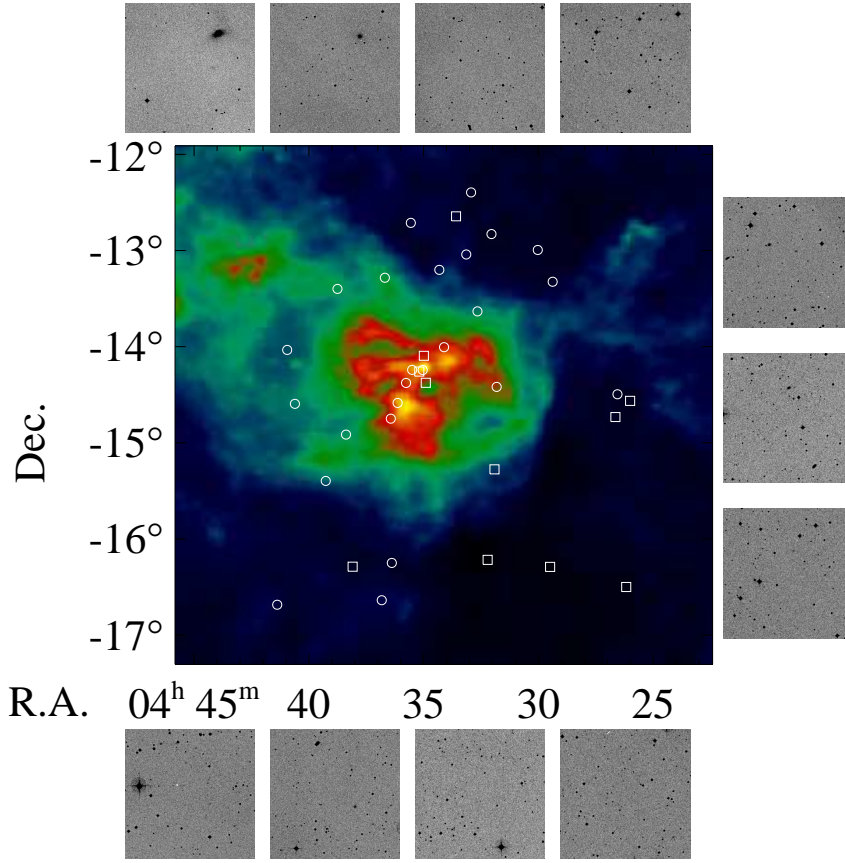


Figure 2. The observed positions in the L 1642 cloud area. superimposed on an IRAS 100 μm map. For details see text.

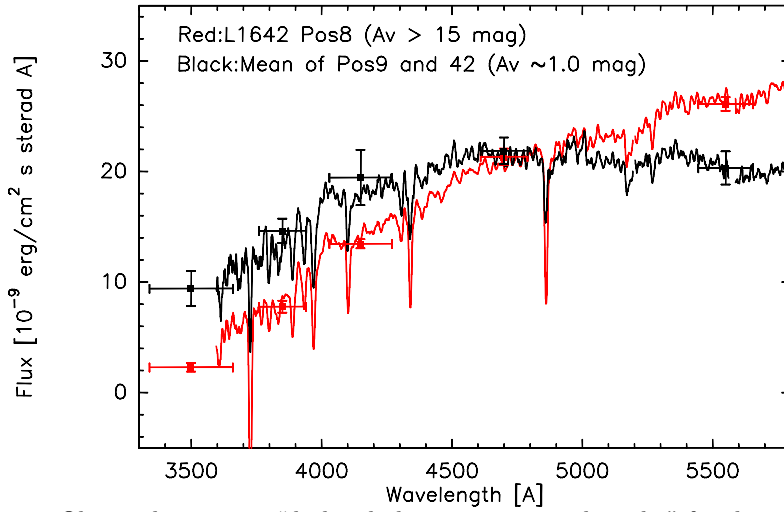


Figure 3. Observed spectrum “dark nebula minus surrounding sky” for the central opaque position #8 and the mean of two translucent positions, #9 and #42.

distribution of stars and dust in the Solar neighbourhood. Such synthetic spectra have been calculated using the model of Mattila (1980) and the recent STELIB library of stellar spectra (Le Borgne et al. 2003). The resulting ISL spectrum, mean over sky, is shown in Fig. 4 (the uppermost blue line). This spectrum, smoothed to our FORS resolution of 1.1 nm, scaled and reddened to correspond to the dark cloud scattered light spectrum, shows several strong Fraunhofer lines and the discontinuity at 400 nm. For the separation of the scattered light we cannot, however, rely on the integrated starlight *model* alone. We have to test and validate this model by observations at intermediate opacity positions of the dark cloud where most of the EBL is transmitted through the cloud and contributes only little to the surface brightness difference “dark cloud minus surroundings”.

3. Separation of the scattered light

The observed surface brightness difference, ΔI , “dark nebula minus surrounding sky” consists of the following main components (followed by + or - depending on whether it makes a positive or negative contribution to ΔI): (1) Starlight scattered by dust in the nebula (+); (2) Starlight scattered by dust in the comparison fields of the surrounding sky (-); (3) diffuse line emission by ionised gas in the comparison fields beyond the distance of the dark cloud (-); (4) the Extragalactic Background Light (present in the comparison fields) (-).

In order to derive an estimate for the EBL it is necessary to separate the contribution of scattered light (components 1 and 2). When applying the dark cloud method to intermediate band photometry, we utilised the 400 nm discontinuity which is strong and well defined in the integrated starlight spectrum and is present also in the scattered light spectra as shown in Fig. 3. However, its value as determined using intermediate bands is strongly influenced by the wavelength-dependent extinction and multiple scattering in the cloud which need to be modeled.

We use our model ISL spectra and the observed VLT/FORS spectrum for the opaque central position #8 to separate the scattered light component. The scattered light spectrum is assumed to be a copy of the ISL spectrum but to be reddened by a factor linearly proportional to the wavelength. We show in Fig. 4 an overall model fit for 360 - 550 nm assuming that $I(EBL) = 2$ cgs at OFF and = 0 at the #8 ON position. The “ON-position” model spectrum (blue line) is the mean ISL spectrum over the whole sky, suitably scaled (by factor 0.18 at 400 nm) and linearly reddened (by 0.075 per 100 nm). The “OFF-position” model spectrum (green line) is the ISL spectrum for $|b| = 37$ deg, scaled according to the wavelength dependent extinction (determined from 2MASS JHK stellar and ISOPHOT 200 μ m surface photometry). The ON minus OFF model spectrum is shown as red line. The observed ON minus OFF spectrum for Pos #8 (as in Fig. 3) is shown as black line. As can be seen the fit is almost perfect except for the Balmer lines. These lines are contaminated by the excess emission of diffuse ionised gas in the OFF positions. At this stage we do not attempt to model this component (shown as magenta line in Fig. 4 on arbitrary scale) and exclude the Balmer lines from our fitting procedure.

4. EBL estimates from the dark cloud method

Although a good fit of the observed spectrum by scattered ISL only can be achieved there are small differences in the depths of the Fraunhofer lines (other than the Balmer Lines) indicating that $I(EBL) \neq 0$. We have made fits over suitably selected narrow wavelength intervals. The EBL is assumed to be constant over the wavelength

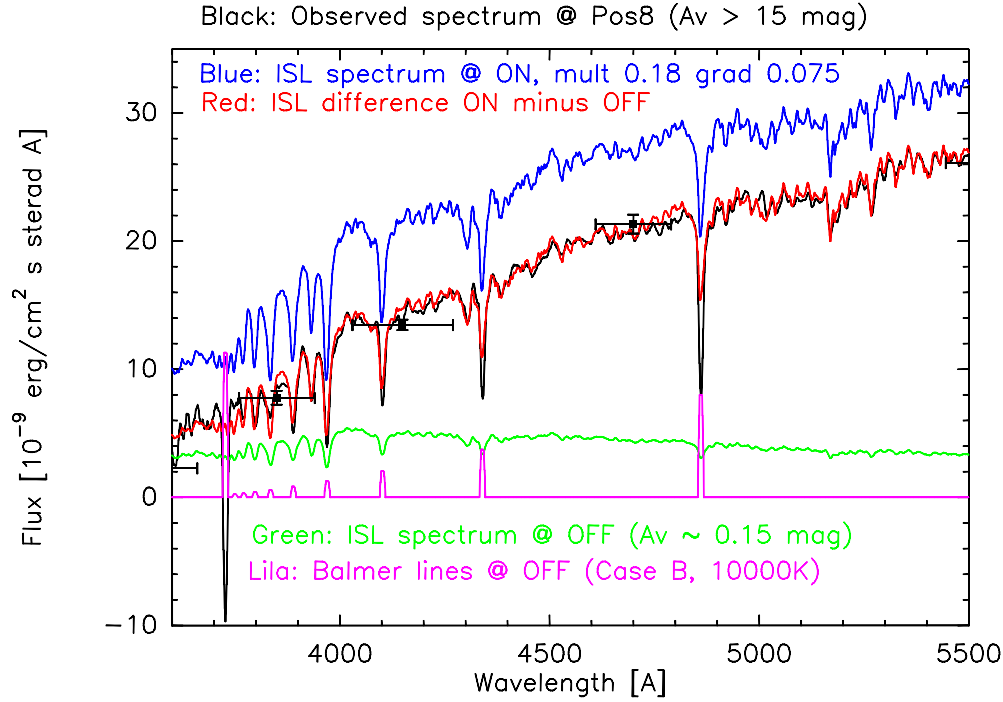


Figure 4. Fitting the central opaque position #8 spectrum with the ISL spectrum.
 $I(\text{EBL}) = 2$ cgs has been assumed for OFF positions. See text for details

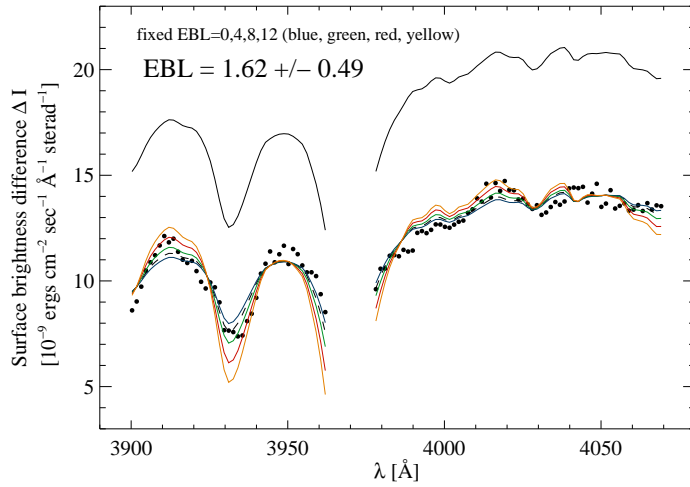


Figure 5. Fitting of the 390 - 407 nm spectral range of the opaque position 8 spectrum with the Integrated Starlight spectrum and different assumed values of the EBL

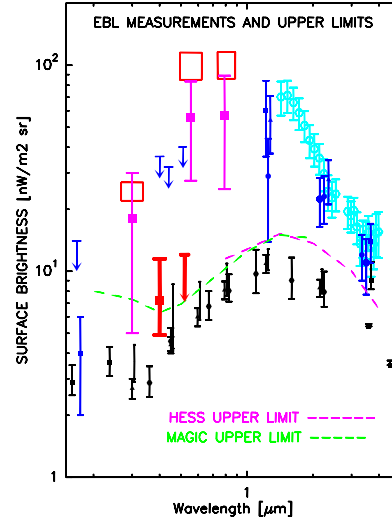


Figure 6. Compilation of current EBL measurements, lower and upper limits.
 See text for symbols

slot in question. The ISL scaling factor and wavelength dependent gradient are free parameters. The fit to the range 390 - 407 nm is shown in Fig. 5. The CaII H line at 396.9 nm was not included because it is contaminated by the He line of ionised gas. Our choice for another suitable slot with strong Fraunhofer lines was 510 - 535 nm. By fitting the observed spectrum with an ISL spectrum and EBL contributions of different amounts we obtain the following EBL values for these two slots:

$$I(EBL)(400 \text{ nm}) = 1.6 \pm 0.5 \text{ cgs } (1\sigma) \text{ or } 6.4 \pm 2.0 \text{ nW m}^{-2} \text{ sterad}^{-1}$$

$$I(EBL)(520 \text{ nm}) \leq 1.6 \text{ cgs } (2\sigma) \text{ or } \leq 8.3 \text{ nW m}^{-2} \text{ sterad}^{-1}$$

The statistical error (1σ) is small enough for putting to the EBL significant limits comparable with the EBL minimum value of $\sim 0.8 - 1.0$ cgs for $\lambda = 360 - 810$ nm derived by summing up deep galaxy counts (Madau and Pozzetti 2000).

Systematic errors. (1) Blocking by the dark cloud is not complete for incident isotropic diffuse radiation like the EBL. For $A_V = 16$ mag the blocking factor is 0.86 (see Mattila 1976, Table A2). (2) The systematic error caused by our ISL model is tested by observing the semi-transparent positions with $A_V \approx 1$ mag for which the scattered starlight has the same spectrum but the EBL contribution is only $\sim 30\%$ of that for $A_V = 15$ mag. They give $I(EBL) \approx 0$ (within 1σ statistical errors) and may thus indicate a need to increase the EBL upper boundary error bar by $\sim 0.3 \times I(EBL)$ or ~ 0.5 cgs.

With a 14% blocking factor correction and increasing the upper bound of the errors (systematic) by 0.5 cgs we end up with the following preliminary EBL estimates:

$$I(EBL)(400 \text{ nm}) = 1.8^{+1.0}_{-0.5} \text{ cgs } (1\sigma) \text{ or } 7.2^{+4}_{-2} \text{ nW m}^{-2} \text{ sterad}^{-1}$$

$$I(EBL)(520 \text{ nm}) \leq 2.3 \text{ cgs } (2\sigma) \text{ or } \leq 12.0 \text{ nW m}^{-2} \text{ sterad}^{-1}$$

We show in Fig. 6 a compilation from UV to NIR (0.1 - 5 μm) of recent EBL measurements and upper limits (colour symbols) as well as lower limits from galaxy counts (black symbols). Upper limits from the TeV gamma-ray absorption method are shown as dashed lines. The resulting values from the present paper are shown as red solid square with error bars at 400 nm and upper limit at 520 nm. The reanalysis by Mattila (2003) of the Bernstein et al. (2002) EBL values are shown as large red rectangles, indicating upper limits. In agreement with these, the reanalysis by Bernstein (2007) resulted in values that were substantially increased from their original estimates. They are shown as the solid magenta squares with error bars. For references to the three upper limits at 400 - 520 nm see Leinert et al. (1998), and for the other points see Mattila (2006) and Dominguez et al. (2011). For a new EBL estimate (not shown in Fig. 6) based on reanalysis of Pioneer10/11 data see Matsuoka et. al. (2011) and these Proceedings.

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